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Abstract— **We investigate packet loss in mobile ad hoc networks via simulation. Ad-hoc on-demand distance vector (AODV) and destination-sequenced distance vector (DSDV) are chosen as representatives of the on-demand and proactive routing protocols respectively. The effects of congestion and mobility in various network contexts are explored. The results indicate that DSDV loses 10% to 20% more packets than AODV does for UDP traffic. For TCP traffic, the packet loss for DSDV is a half of that for AODV. Mobility is the dominant cause for AODV, which is responsible for more than 60% of total packet loss. For DSDV, more than 50% of total packet loss is congestion-related. Sample data shows that the packet loss distribution over time is bursting, which makes the tradition Poisson framework unsuitable for modelling it. Preliminary results exhibit self-similar pattern that leads us to believe that fractal model is promising to describe packet loss in ad hoc networks. This work provides guidelines for the design of routing and flow control algorithms and insights in choosing proper parameters in future simulation and analytic studies.**

Index Terms— **ad hoc network, packet loss, routing protocol, congestion, mobility**

I. Introduction

Throughput is generally accepted as one of the most important metrics to evaluate the performance of a routing protocol. Several simulation-based performance comparisons have been done for ad hoc routing protocols in the recent years. S.R. Das et al. evaluate performance of ad hoc routing protocols based on the number of conversations per mobile node [1]. The performance comparison of two on-demand routing protocols: dynamic source routing (DSR) [2] and AODV [3] is presented in [4]. The performance of two location-based routing protocols for ad hoc networks is investigated in [5]. An adaptive distance vector routing algorithm is proposed in [6], and its performance, compared with AODV and DSR, is studied. Although various throughput results in different network contexts have been obtained, the causes for throughput variation in ad hoc networks has not been deeply understood. Packet loss is one thrust to study throughput, since throughput is determined by how many packets have been sent and how many packets have lost.

Packet loss in wired network has been investigated. For example, a single server queueing system with a finite buffer capacity is used to analyze packet loss processes in high-speed networks in [7]. The end-to-end packet delay and loss behaviors in the Internet are studied using the UDP echo tool in [8]. These work target at the packet loss due to buffer overflow (congestion), which is the major loss in wired networks.

Packet loss problem is much more complicated in mobile ad hoc networks, because wireless links are subject to transmission errors and the network topology changes dynamically. A packet may lose due to transmission errors, no route to the destination, broken links, congestions, etc. The effects of these causes are tightly associated with the network context (e.g., host mobility, number of connections, traffic load, etc.). Even building an approximate model to analytically evaluate packet loss is difficult. We investigate the problem via simulations. Data is gathered from more than 1000 individual experiments to estimate the desired true characteristics of packet loss in ad hoc networks.

In mobile ad hoc networks, wireless link transmission errors, mobility, and congestion are major causes for packet loss. Packet loss due to transmission errors is affected by the physical condition of the channel, the terrain where networks are deployed, etc. They can not be eliminated or reduced by improving the routing protocols. This paper only addresses congestion-related and mobility-related packet loss. Congestion in a network occurs whenever the demands exceed the maximum capacity of a communication link, especially when multiple hosts try to access a shared media simultaneously. Mobility may cause packet loss in different ways. A packet may be dropped at the source if a route to the destination is not available, or the buffer that stores

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pending packets is full. It may also be dropped at an intermediate host if the link to the next hop has broken. We study the effect of congestion and mobility on packet loss in various network contexts. AODV and DSDV [9] are chosen as representatives of on-demand and proactive routing protocols respectively.

This work can benefit the design of routing and flow control algorithms, the dimensioning of buffers, identifying and avoiding the performance bottleneck of current routing protocols, and choosing proper parameters in future simulation and analytic studies.

The rest of the paper is organized as follows. Section II introduces the related work. The simulation model, including the simulation environment, mobility, traffic, routing protocols, congestion-related and mobility-related packet loss, are discussed in section III. Section IV presents two sets of experiments and the results. The relations between shortest path and congestion, and packet loss distribution are discussed in section V. Section VI concludes the paper.

II. Related Work

There has been some recent work on addressing packet loss issues in wireless networks. S. Biaz and N.H. Vaidya investigate the ability of three loss predictors to distinguish congestion losses from wireless transmission losses [10]. They use a wireless link with transmission loss rate r_w in the simulations. F. Anjum and L. Tassiulas analytically study the performance of different TCP algorithms over a wireless channel with correlated packet losses [11]. A simple two-state Markov chain is used to model the correlated fading channel. T.V. Lakshman et al. also analyze the impact of random packet loss at a wireless link on the performance of TCP/IP in [12]. They indicate that bidirectional congestion increases TCP's sensitivity to loss. These efforts assume transmission losses on a single wireless link follow a simple model and focus on how losses effect the performance of TCP.

Even if wireless transmission is loss-free, packet loss still exists in ad hoc networks. Our work is to understand the major causes for packet loss and to capture its characteristics.

III. Simulation Model

We use the network simulator ns-2 (version 2.1b9) for our simulation study.

A. Environment

Each mobile host uses an omni-directional antenna having unity gain. The wireless interface works like the 914 MHz Lucent WaveLAN direct-sequence spread-spectrum (DSSS) radio interface [13]. WaveLAN is modeled as a shared-media radio with a nominal bit rate of 2 Mb/s, and a nominal radio range of 250m [4]. The IEEE 802.11 distributed coordination function (DCF) is used as the MAC layer protocol. A unicast data packet destined to a neighbor is sent out after handshaking with request-to-send/clear-to-send (RTS/CTS) exchanges and followed by an acknowledgement (ACK) packet. The broadcast packets are simply sent out without handshake and acknowledgement. The implementation uses carrier sense multiple access with collision avoidance (CSMA/CA).

B. Mobility

We use the *random waypoint* model [14] to generate movements of mobile hosts. At the beginning of a simulation, mobile hosts are randomly placed on 1000m x 1000m a square field. Each host randomly chooses its destination in the field, and a moving speed that ranges from 0 to 20 m/s. All destinations and speeds are independent and identically distributed. Every host repeats the above step after it has reached the destination and waited a specified time (the pause time). According to this model, the speed and direction of the next movement have no relation to those of the previous movement. As indicated in [15], the pause time and the maximum speed have similar impacts on the mobility with respect to link change or route change. Thus the mobility is varied by changing the pause time in the simulation.

C. Traffic

To investigate the impact of traffic load and congestion control mechanisms on packet losses, both unresponsive traffic and responsive traffic are studied.

- *Unresponsive traffic* only consists of UDP connections, each of which is specified as a source-destination (S-D) pair. Every source is associated with a constant bit rate (CBR) traffic generator, which sends out packets at the given rate. The source of each S-D pair is randomly chosen from all hosts, and the destination is randomly chosen from all hosts other than the source. All S-D pairs are mutually independent. The packet size is fixed at 512 bytes. The start time of each connection is uniformly distributed between 0 to 100 seconds.
- *Responsive traffic* is comprised of TCP connections. Each connection has a Tahoe TCP [1] sender and a

[1]The TCP performs congestion control and round-trip-time estimation in a way similar to the version of TCP released with the 4.3BSD Tahoe UNIX system from UC Berkeley, so it is called Tahoe TCP.

base TCPSink receiver. The sender window size is decreased by half when packet losses are detected. The retransmission starts from the first lost packet. Tahoe TCP enters the slow start when an ACK for a new packet is received. All TCP packets have the same size of 512 bytes. The initial sender window size is 1 and the maximum bound on the window size is 32. TCPSink is responsible for returning ACKs to the sender. It generates one ACK per packet received. The ACK packet size is 40. The data of each connection is generated by an attached FTP application, which simulates a bulk data transfer. Every FTP application starts at a time randomly chosen from 0 to 100 seconds.

D. Routing Protocols

The routing protocol greatly affects packet loss besides mobility and traffic. All properties of a routing protocol, such as what routing information is maintained, the way in which the information is obtained, how to choose a route, etc., may have different effects. The experiments are conducted by using DSDV and AODV routing protocols. These two protocols share a lot of properties. The largest difference between them is that DSDV is a proactive while AODV is on-demand.

DSDV extends the basic Bellman-Ford mechanism by attaching a sequence number, which is originated by the destination, to each distance. This destination sequence number is used to determine the "freshness" of a route. Routes with more recent sequence numbers are preferred for making packet forwarding decisions by a host, but not necessarily advertised to other hosts. For routes with the equal sequence number, the one with the smallest distance metric is chosen. Each time a host sends an update to its neighbors, its current sequence number is incremented and included in the update. The sequence number is disseminated throughout a network via update messages. The DSDV protocol requires each host to periodically advertise its own routing table to its neighbors. Updates are transmitted immediately when significant new routing information is available. Routes received in broadcasts are used to update the routing table. The receiver adds an increment to the metric of each received route before updating.

AODV routing protocol is also based upon distance vector, and uses destination sequence numbers to determine the freshness of routes. It operates in the on-demand fashion, as opposed to the proactive way of the DSDV protocol. AODV requires hosts to maintain only active routes. An *active route* is a route used to forward at least one packet within the past *active timeout* period.

	Mobility-related	Congestion-related
MAC Layer	√	√
Network Layer	√	

TABLE I
PACKET LOSS AT MAC AND NETWORK LAYERS

When a host needs to reach a destination and does not have an active route, it broadcasts a Route Request (RREQ), which is flooded in the network. A route can be determined when RREQ is received either by the destination itself or by an intermediate host with an active route to that destination. A Route Replay (RREP) is unicast back to the originator of RREQ to establish the route. Each host that receives RREQ caches a route back to the originator of the request, so that RREP can be sent back. Every route expires after a predetermined period of time. Sending a packet via a route will reset the associated expiry time.

E. Differentiated Packet Losses

Packet loss is measured at all mobile hosts. Every host monitors the networking layer and the MAC layer for all kinds of packet losses. The layers of the protocol stack and the modules that are responsible for mobility-related and congestion-related packet loss are identified, as shown in table I.

Mobility-related packet loss may occur at both the network layer and the MAC layer. When a packet arrives at the network layer, the routing protocol forwards the packet if a valid route to the destination is known. Otherwise, the packet is buffered until a route is available. A packet is dropped in two cases:

- The buffer is full when the packet needs to be buffered.
- The time that the packet has been buffered exceeds the limit. (The AODV implementation in ns-2 poses a 30-second limit on the time a packet can be buffered. The DSDV implementation does have a limit.)

The MAC layer mobility-related packet loss occurs when the next hop of a packet is out of range at the moment the packet is sent by the MAC protocol. The reason is that the routing information is obsoleted. It occurs frequently in a high mobility network than in a low mobility network.

Congestion-related packet loss only occurs at the MAC layer. Because CSMA/CA is used in the simulation, a packet may be dropped due to congestion for two reasons:

- The wireless channel is so busy that the times of *back off* exceed the limit.
- The channel is associated with a queue that buffers all the packets waiting to be sent. When the queue is full, any coming packet is dropped.

IV. Experiments

A series of experiments have been conducted to investigate mobility-related and congestion-related packet losses in different network contexts. The network configuration for the experiments is a 1000m x 1000m square field with 30 hosts. The buffer size is 64-packet for each route and MAC layer. Each data point in the result figures represents an average of 5 runs with identical traffic but different mobility scenarios, which are randomly generated with the same parameters (i.e., same maximum speed and pause time). Every experiment runs for at least 1000 seconds.

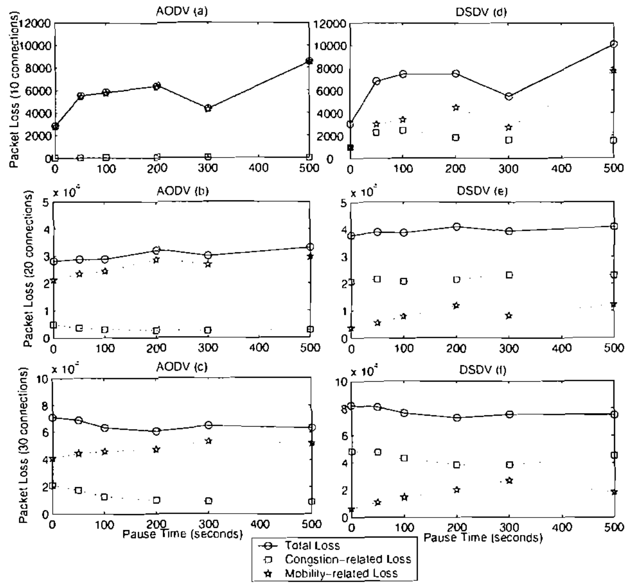

Fig. 1. Packet loss for 4 packets/s CBR connections

A. Varying Mobility and Communication Request

The purpose of the first set of experiments is to study the impact of host mobility. Pause time is varied over the range of {0, 50, 100, 200, 300, 500} seconds. Zero pause time results in the highest mobility since hosts keep moving without a pause. For these experiments, 10, 20, and 30 connections, which represent light, moderate, and heavy communication requests respectively[2], are used. The packet sending rate for each connection is 4 packets/s. The results are shown in figure 1.

1) Packet Loss for AODV: Total packet loss grows from about 3000 to 8000 with the increase of pause time from 0 to 500 seconds for 10 connections, as shown in figure 1a. In case there are 20 connections, total packet loss gradually increases by 10% (figure 1b). For 30 connections, it gradually decreases by 10% (figure 1c). As the communication request grows from 10 to 20, total packet loss increases by 9 times when pause time is 0 seconds, and by 3 times when pause time is 500 seconds. The increase of communication request from 20 to 30 results in doubled total packet loss.

There is almost no congestion-related packet loss when the communication request is 10. In the other two cases, packet loss gradually decreases by about a half as pause time increases from 0 to 500 seconds. From 10 to 20 and 30 connections, with no pause time, packet loss increases to 5000 and 20000 respectively. The percentage with respect to total loss increases as well, to 20% and 30% respectively.

[2]Traffic load is represented by the sending rate in this paper. It has different effect on packet loss compared with communication request.

Mobility is always the dominant cause for packet loss. However, the majority decreases as the communication request increases. When pause time is 0 seconds, the percentage of mobility-related loss decreases from about 100% to 70% and 60%, given 10, 20, and 30 connections. The absolute value and the percentage of mobility-related packet loss increase with pause time.

2) Packet Loss for DSDV: The growth of total packet loss with pause time for DSDV follows a similar pattern as that for AODV. For 10 connections, total packet loss increased from about 3000 to 10000 as pause time increases from 0 to 500 seconds (figure 1d). It is nearly unchanged with pause time for 20 and 30 connections as shown in figure 1e and 1f (gradually increases by 5% for 20 connections and decreases by 5% for 30 connections). Increasing communication request from 10 to 20 results in total packet loss grows 10 times and 4 times for 0 and 500 seconds pause time, respectively. The increase of communication request from 20 to 30, however, only doubles the total packet loss.

The percentage of congestion-related packet loss increases with communication request. Congestion begins to be the dominant cause for packet loss after communication request reaches 20 (it results in approximate 50% and 60% total packet loss with 20 and 30 connections, respectively). The loss is fairly stable with pause time, but jitters exist.

Mobility-related packet loss increases with communication request, but slower than congestion-related packet loss does.

3) Packet Loss Comparison for AODV and DSDV: The comparison of different packet losses for AODV and DSDV is as follows.

- **Total packet loss:** The total packet loss for DSDV is always 10% to 20% higher than that of AODV, regardless pause time or number of connections. For moderate and heavy communication requests, total packet loss for DSDV is more stable than that of AODV with the increase of pause time.
- **Congestion-related packet loss:** DSDV loses more packets due to congestion than AODV does. The gap of congestion-related packet loss between DSDV and AODV decreases with the growth of communication request.
- **Mobility-related packet loss:** AODV has more mobility-related packet loss than DSDV does.

B. Varying Traffic Load and Traffic Type

The second set of experiments illustrate the effect of traffic load and traffic type. Pause time ranges over {0, 50, 100, 200, 300, 500} seconds. 10, 20 and 30 connections are used. Both unresponsive traffic and responsive traffic are studied. The packet rate for CBR connections is 8 packets/s, which injects a reasonable heavy load to the network. We use the same mobility scenarios and connection configurations for this set of experiments as for the previous set of experiments to compare the results with the previous ones.

1) CBR connections with 8 packets/s: As shown in figure 2, each curve that represents a different type of packet loss has similar shape as the corresponding one in the previous experiments, but flatter (i.e., increase and decrease are more gradually).

For AODV, mobility is still the major cause for packet loss. Congestion plays a more important role compared with CBR connection with 4 packets/s rate. Increasing number of connections has less effect in this set of experiments than in the previous one. From 10 connections to 20 connections, total packet loss increases by only about 3 times. From 20 to 30 connections, the increase is less than 2 times. Comparing figure 2a with figure 1a, total loss increases by 660% for 0 second pause time, and by 200% for 500 seconds pause time. For moderate and heavy communication requests, total packet loss is only tripled or doubled as packet rate increases from 4 to 8 packets/s.

For DSDV, congestion dominates packet loss even when there are only 10 connections. Total packet loss increases the same amount as that for AODV when communication request increases, with respect to percentage. Total packet loss with traffic load is almost the same for DSDV and AODV.

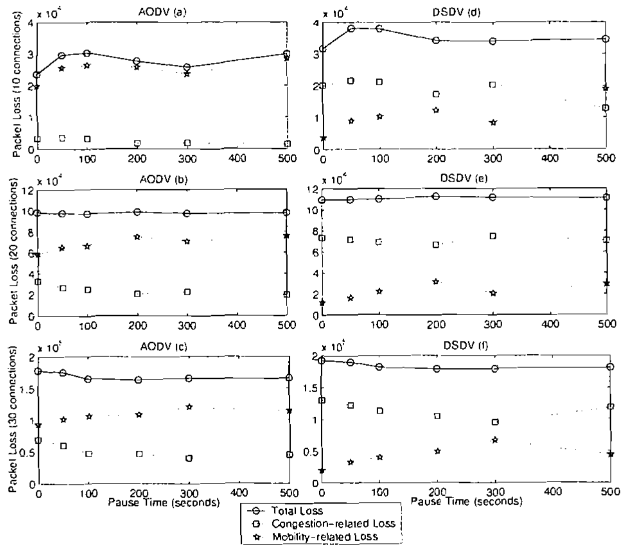

Fig. 2. Packet loss for 8 packets/s CBR connections

For both AODV and DSDV, increasing communication request has similar impact on total packet loss (i.e., more losses) as increasing traffic load. The increase of either parameter will result in decreasing the impact of the other parameter. Heavier communication request or traffic load introduces more congestion-related packet loss.

2) TCP connections: Number of bytes (the total size of all lost packets), instead of number of packets, is used in experiments with TCP connections. Because both application data and ACK packets, which have different sizes, are treated as data packets by the routing protocol, the number of bytes is more comprehensive than the number of packets.

Figure 3 demonstrates byte loss in TCP connections[3]. It shows that the congestion-related loss for both protocols is greatly reduced by the congestion control mechanism. Total loss decreases with the decrease of mobility. DSDV outperforms AODV in terms of total loss. Total loss of DSDV is only half of that of AODV in all test cases, because the effect of the major cause for DSDV to lose packets (i.e., congestion) is offset by the congestion control mechanism.

For AODV, with the decrease of congestion-related loss, more than 90% of total loss is mobility-related. The total effect of mobility and congestion is less than 20% for DSDV.

To improve throughput, different routing protocols require different mechanisms to remedy the major causes

[3]The difference of the amounts of bytes sent by AODV and DSDV is smaller than 5%.

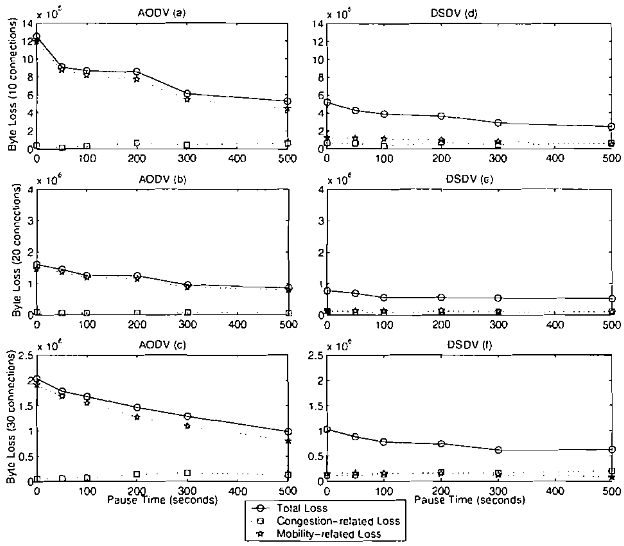

Fig. 3. Packet loss for TCP connections

for packet loss. Specifically, integrating congestion control techniques with DSDV will significantly improve the throughput, as shown in figure 3. For on-demand routing protocols like AODV, fast rediscovery of new routes will reduce mobility-related packet loss, and gain higher throughput consequently. S.R. Das et al. proposed ad hoc on-demand multipath distance vector (AOMDV) protocol to decrease the route discovery latency [16]. Their result showed that AOMDV loses fewer packets than AODV (3-5% less).

V. Discussions

The simulation results bring out some interesting facts and give rise to several important problems. They are discussed in this section.

A. Shortest Path and Congestion

Figure 1 and 2 show that DSDV loses much more packets due to congestion than AODV does. Since the per connection traffic load is much lighter (less than 8 packets/s = 32Kb/s) than the communication capacity of a host (2Mb/s), the occurrence of congestion indicates that connections converge on heavily burdened hosts. The converged traffic load exceeds the capacity of those hosts. This difference may result from, with a very great chance, the different route maintenance schemes used by DSDV and AODV, because both protocols use distance vector to represent routing information and choose the routes based on the shortest paths, . In a mobile ad hoc network, hosts keep moving. The shortest path between a source and a destination may change as time passes. DSDV requires periodical updates of routing information. Every host has the most recent knowledge about routes. It is likely that the path chosen to forward packets is the currently shortest one. In contrast to DSDV, AODV picks up a path (usually the shortest one) when a host initiates a route discovery. The host keeps sending packets via this path until it breaks, even if shorter paths become available after route discovery.

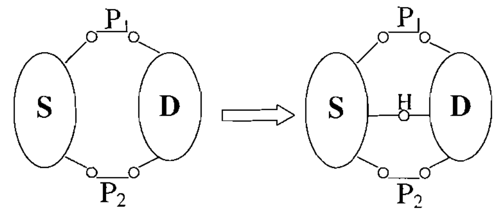

Fig. 4. Shortest path and congestion

The difference between these two strategies can be illustrated with figure 4, in which S is a set of source hosts and D is a set of destination hosts. P_1 and P_2 are two shortest paths between S and D. Originally, both DSDV and AODV send packets from S to D through these two paths. At time t, a host H moves in between S and D, and a shorter path is available. AODV still sends packets via P_1 and P_2. DSDV, however, sends all packets through the new path once it finds out the new one is shorter. Congestion may occur at host H when traffic load exceeds its capacity. This example shows that keeping sending packets through the shortest path may cause congestion.

B. Packet Loss Distribution over Time

The figures presented in section IV provide statistical results of packet loss over the simulation time. We further investigate the packet loss problem by exploring answers to the following two research questions.

- What is the distribution of packet loss? What are the characteristics of the distribution?
- Is packet loss evenly distributed over all hosts? What is the distribution of packet loss at a specific host over the time?

Another experiment is conducted to study the packet loss distribution. Sample data is collected every 10 seconds. 20 CBR connections with a rate of 4 packets/s are used. Pause time is 50 seconds. DSDV is used as the routing protocol because it has comparable congestion-related and mobility-related packet losses. To get enough sample data, the simulation runs for 2500 seconds.

Figure 5 shows the distributions of total packet loss at mobile hosts with ID 0, 10, and 20 (every host is given

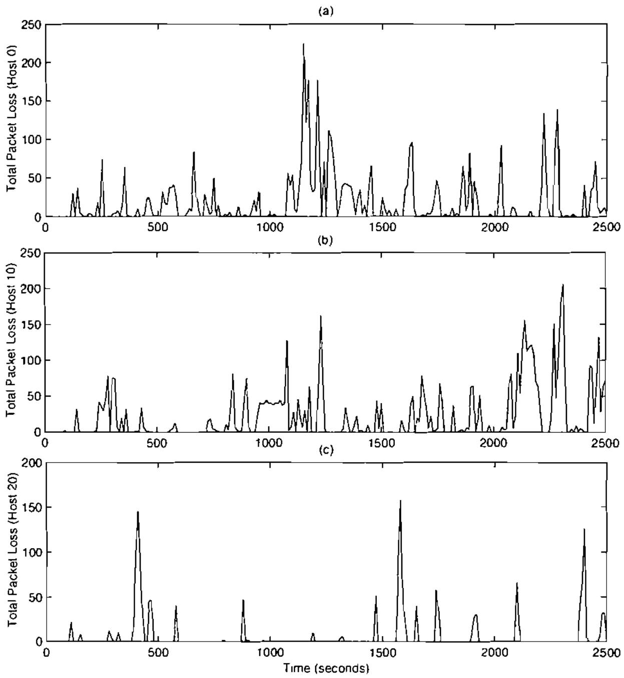

Fig. 5. Packet loss distribution for individual hosts

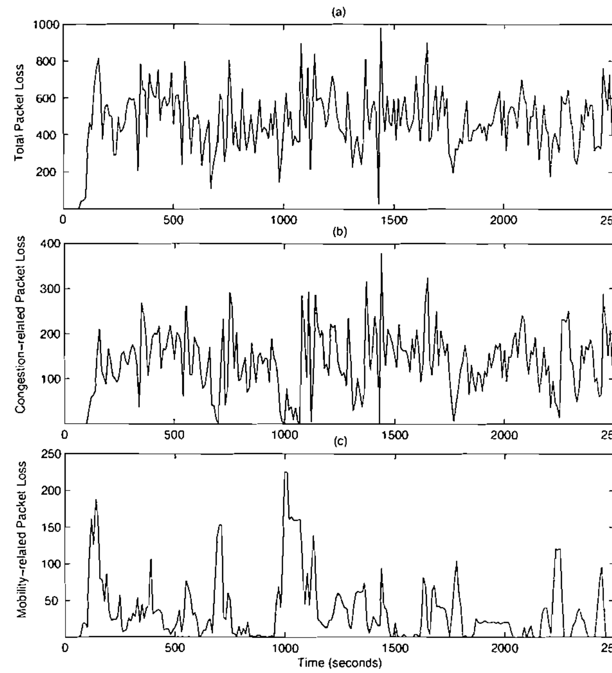

Fig. 6. Network-wide packet loss distribution

an ID at the beginning of the simulation without any bias). The curves fluctuate over the time, like pulses with random peaks. From this figure, packet losses at these three hosts seem to be independent. They have different highest values (230, 200, and 150) and different number of peaks. The peaks are reached at different time slots.

The result helps in dimensioning packet buffer for ad hoc network routing protocols. For example, from the bursting pattern of packet loss shown in the figure, we can conclude that a larger buffer will not help much in reducing packet loss if the size is fixed, because packet loss varies a lot from one time to the next. This conclusion is supported by the experiment conducted in [15], which shows that increasing the buffer size from 5-packet to 64-packet does not increase the throughput for DSDV.

Figure 6 shows the distributions of network-wide total packet loss, congestion-related loss, and mobility-related loss. Every kind of packet loss fluctuates over the simulation time. All exhibit bursting behaviors. The maximum numbers for total packet loss, congestion-related packet loss, and mobility-related packet loss are about 1000, 400, and 230 respectively.

Packet loss cannot be described by the traditional Poisson-based model, which is widely used in network traffic modelling. The Poisson framework cannot capture the burstiness presented in figure 5 and 6. We tend to believe that packet loss is *self-similar*. Figure 6a and 6b exhibit a *fractal-like* pattern. This pattern is illustrated in figure 7. Figure 7a and 7c show the numbers of total packet loss and congestion-related packet loss sampled every 100 seconds, respectively. Figure 7b and 7d show the corresponding numbers sampled every 10 seconds. Comparisons between 7a and 7b, 7c and 7d indicate some extent of similarity.

We are working on getting a large traffic traces (more than 100,000 seconds) so that the observation scaling range can span more than 3 decades. We hope to obtain convincing evidence of fractal-like scaling for packet loss in mobile ad hoc networks.

VI. Conclusions and Future Work

To our knowledge, this work is the first attempt towards a comprehensive investigation of packet loss in mobile ad hoc networks. The contributions of congestion and mobility to the total packet loss have been examined. The impacts of host mobility, communication request, traffic load, traffic type, and AODV and DSDV routing protocols have been studied. The simulation results indicate:

- Mobility is the dominant cause for AODV, which is responsible for more than 60% of total packet loss. For DSDV, more than 50% of total packet loss is congestion-related.

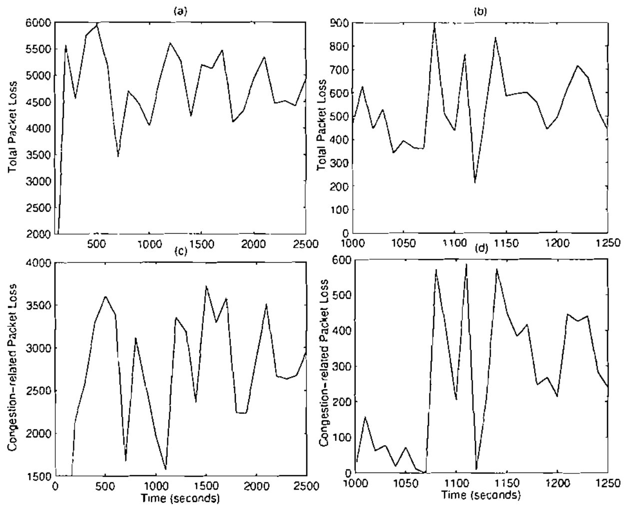

Fig. 7. Network-wide packet loss over two orders of magnitude

- DSDV loses 10% to 20% more packets than AODV does for UDP traffic. For TCP traffic, the packet loss for DSDV is a half of that for AODV. DSDV outperforms AODV because the congestion control mechanism of TCP greatly reduces congestion-related loss.
- Increasing communication request or traffic load has a stronger impact on packet loss in the less stressful situation (i.e., 10 connections at a rate of 4 packets/s).
- Host mobility decreases packet loss, given light communication request and traffic load. For other cases, packet loss is rather stable with host mobility.
- Always sending packets via the shortest path may cause congestion at a few heavily burdened hosts.
- Packet loss distribution over time exhibits certain extent of self-similar pattern.

Inspired by this work, we are interested in investigating the relationship between shortest path and congestion. We are working on a loss sensitive routing protocol to support network layer congestion control for both UDP and TCP traffic. We are studying whether packet loss process has fractal characteristics. Our ultimate goal is to build a solid foundation for the research on routing and flow control algorithms for mobile ad hoc networks.

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